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LOW POWER UNATTENDED DEFENSE REACTOR

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ABSTRACT

A small, low power, passive, nuclear reactor electric power supply has been designed for unattended defense applications. Through innovative utilization of existing proven technologies and components, a highly reliable, "walk-away safe" design has been obtained. Operating at a thermal power level of 200 kWt, the reactor uses low enrichment uranium fuel in a graphite block core to generate heat that is transferred through heat pipes to a thermoelectric (TE) converter. Waste heat is removed from the TEs by circulation of ambient air. Because such a power supply offers the promise of minimal operation and maintenance (O&M) costs as well as no fuel logistics, it is particularly attractive for remote, unattended applications such as the North Warning System (1).

REACTOR POWER SUPPLY CONCEPT

The low power unattended defense reactor is a 20% enriched uranium-fueled, graphite-moderated, thermal-spectrum reactor cooled by heat pipes. TE elements attached to the heat pipes convert part of the 200 kWt of heat into electric power and reject waste heat to ambient air flowing past fins connected to the TEs (see Fig. 1). The power supply can provide 20 kWe at beginning of life (BOL), 15 kWe of which is for the normal load, 1.5 kWe is for air circulating fan power, and the remainder is a contingency for TE power degradation over lifetime. Sufficient fuel is

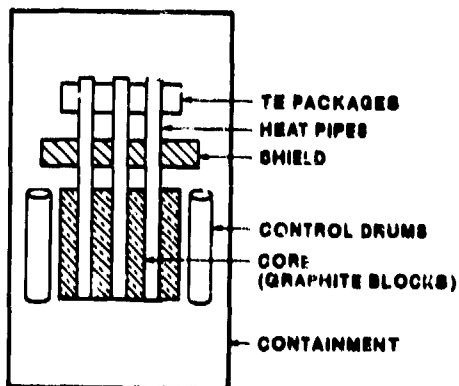


Fig. 1. Reactor system schematic.

incorporated in the reactor to allow 20 years of normal operation without refueling.

This inherently safe reactor has several salient features. There are few moving parts, thus giving the system high reliability. The reactor is "walk-away safe" and has no fuel logistics. Because the power supply assimilates existing, proven component technologies, no major development is required. The spherical particle fuel used has excellent fission product retention capability and is quite similar to that currently produced for high temperature gas cooled reactors. Redundant heat pipes and TEs allow for failures in either or both components with little reduction in electrical output. Through the use of ambient air to cool the cold side of the TEs, the need for an intermediate coolant loop is eliminated. Redundant air circulation fans provide forced convection cooling for maximum power output from the system.

As shown in Fig. 2, the reactor is contained in a concrete vault and rests on a concrete pad. Heat pipes with contiguous TEs extend above the reactor in a manner not unlike a chimney. Local rock and earth, where available for shielding, are piled around the

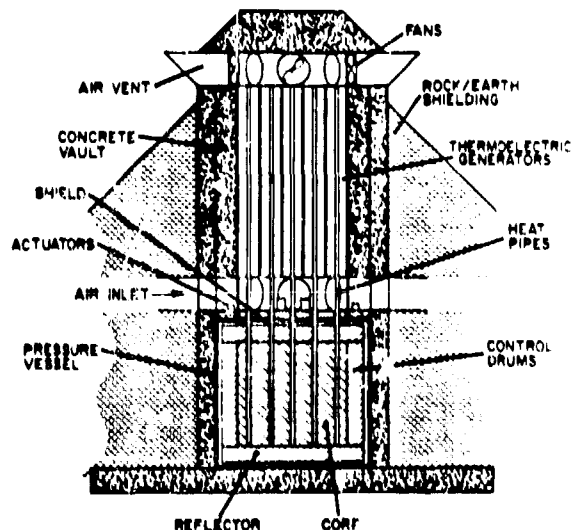


Fig. 2. Low power unattended defense reactor.

reactor in a conical pattern. The overall power supply is 5.5 m high and 10 m wide at the base.

REACTOR

The heart of the power supply is the reactor core, with its 20% enriched uranium, UCO particle fuel. In addition to being relatively easy to handle and fabricate, the fuel particles are stable to 1400°C and very high burnup (100,000 MWd/ton). Because normal core maximum temperature is 640°C and the end-of-life burnup is approximately 30,000 MWd/ton, considerable operational and safety margins exist.

1. Fuel. The reactor fuel is based on available technology. The fuel consists of UCO spherical particle kernels 350 μm in diameter that are coated by porous carbon, pyrolytic carbon, silicon carbide (SiC), and pyrolytic carbon to form a quadruple layer. The layers constitute a spherical shell 800 μm in diameter, which is called a "Triso" particle, as shown in Fig. 3. The paramount feature of the Triso fuel particle is its ability to retain virtually all of the fission products generated within the kernel up to a temperature of 1400°C. Even under extremely severe accident conditions in which the fuel reaches a temperature of 2100°C, 90% of the particles will not fail. The Triso particles are mixed with graphite binder and pressed into cylindrical fuel rods 1.3 cm diameter and 4 cm long for loading into the core.

The reactor core consists of a 125 cm diameter, H-451 graphite block 125 cm high, as shown in Fig. 4 (a segmented block core is also an option). Holes are bored in the block for approximately 1000 fuel rod stacks, 19 heat pipes, and 6 secondary B₄C shutdown mechanisms. The volume ratio of graphite to fuel rods in the core is 9 to 1. The volume ratio of graphite to UCO is about 250 to 1. The core is surrounded by a 20-cm thick graphite circumferential reflector and by similar axial reflectors on top and bottom. This configuration produces a thermal neutron spectrum reactor. The core contains 11 kg of ²³⁵U, of which 1.4 kg is consumed over the 20-year lifetime.

2. Reactivity Analysis. Reactor control is provided by 18 control drums in the reflector. Although mostly graphite, the drums contain 120 degree circular ¹⁰B₄C segments, which when rotated in toward the core provide neutron absorption, reducing reactivity (k_{eff}). Electromechanical actuators situated atop the reactor are used to rotate the drums. The actuators contain electric brakes that prevent drum movement unless deactivated. Should a complete power

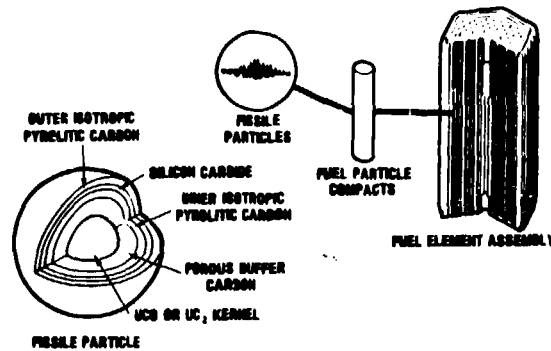


Fig. 3. HTGR fuel element components.

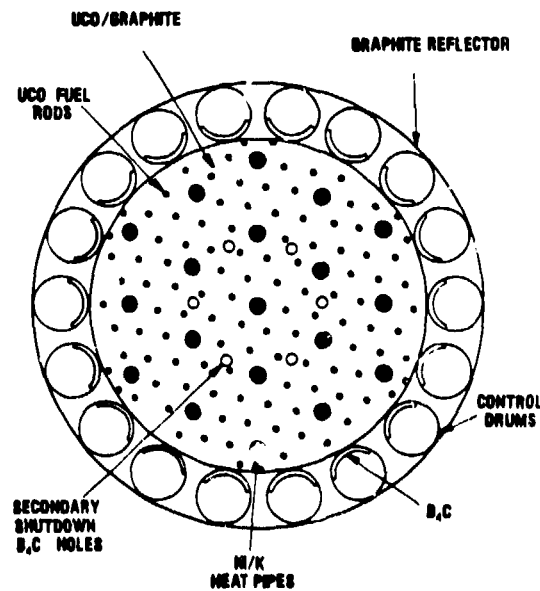


Fig. 4. Reactor graphite block core.

failure occur, springs return all drums to the "in" position. The drums are fitted with mechanical locks that prevent drum movement thereby assuring subcriticality during assembly and transportation. A second set of mechanical drum locking pins is used to increase safety by restricting drum rotation to a partial out condition during the early years of the reactor life. As burnup proceeds, in later years, the second set of locking pins is removed allowing the drums to rotate to the full out position.

A second independent emergency reactor shutdown system is incorporated in the design. It consists of six containers of ¹⁰B₄C spheres that reside atop the

reactor during normal operation. Fusible diaphragms hold the spheres in place. If an emergency situation should occur, and the reactor temperature rises to a level at which the diaphragms melt, the $^{10}\text{B}_4\text{C}$ spheres enter the six normally void holes in the core. Sufficient negative reactivity exists when the balls are in the core to render the reactor subcritical even when all drums are in the full out position.

Extensive computer neutronics calculations have been performed on the reactor. Both multigroup transport theory (TWODANT) and Monte Carlo methods (MCNP) have been used. With the control drums in the full "out" position, calculations show that the k_{eff} equals 1.11. Calculations also show $k_{\text{eff}} = 0.98$ when the drums are at the "in" position. Insertion of the B_4C particles into the core further reduces k_{eff} to 0.74. Table I is a compendium of values for k_{eff} and Δk_{eff} .

With a $\text{C}/^{235}\text{U}$ atom ratio of 4000/1, the reactor has a nearly thermal energy neutron spectrum; 80% of the fissions are produced by thermal neutrons. The radial and axial power distributions at the core center and edges are shown in Fig. 5 for a non-power-flattened core. The overall maximum/average and minimum/average power densities are 1.73 and 0.52, respectively. Subsequent core design will judiciously position the fuel rods and heat pipes to achieve a high degree of power flattening and constant power per heat pipe.

Calculations were performed to estimate reactivity changes associated with the core temperature increase during startup as the temperature rises from ambient to 630°C average operating temperature. The results, which also include fuel burnup, are shown in Table I. The various components of the reactor temperature coefficient are shown in Fig. 6. Heating of the graphite moderator produces higher energy thermal neutrons. Because the fuel absorption cross section is lower at the elevated energies, the neutrons tend to preferentially leak from the core. This effect accounts for most of the reactivity loss at high temperatures. Increased capture in ^{238}U resonances also contribute to a significant reactivity decrease. At the expected average core operating temperature of 630°C the total reactivity loss is estimated to be 6.8% Δk_{eff} .

The reactivity loss due to fuel depletion and fission product buildup, assuming 20-years operation at 200 kWt, was estimated to be 4.6%. The single most absorptive fission product is ^{149}Sm . Based on the above calculations, a total BOL excess reactivity of about 11% is required to compensate for

TABLE I
REACTIVITY TABLE

Condition	k_{eff}
Drums Out, BOL	1.11
Drums In, BOL	0.98
Drums In, B_4C Balls in	0.74
<u>Cold-to-Hot at 630°C</u>	
	Δk_{eff}
Thermal Base	0.045
^{238}U Doppler	0.020
Expansion	0.003
Total	0.068
<u>Burnup (20 yr at 200 kWt)</u>	
^{235}U	0.020
^{149}Sm	0.010
Other FP	0.016
Total	0.046

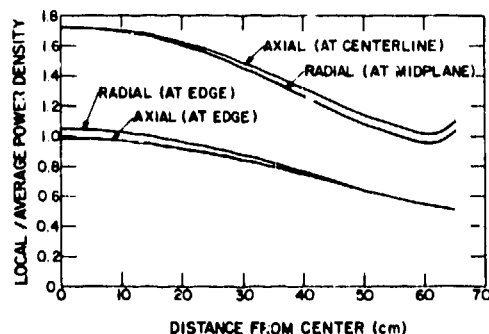


Fig. 5. Power distribution for a non-power flattened core.

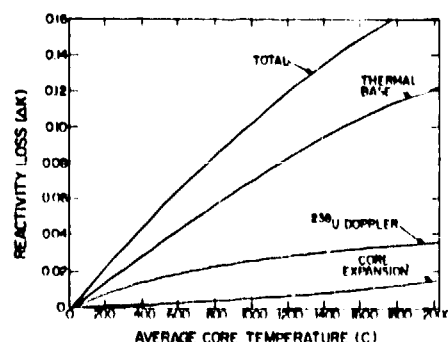


Fig. 6. Reactivity loss vs average core temperature.

temperature effects and fuel burnup. Based on the calculated control drum worth of 13% reactivity, the BOL shutdown margin with control drums fully inserted is -2% ($k_{eff} = 0.98$). Additional shutdown margin will be obtained by incorporating burnable poisons in the form of Gd_2O_3 to offset the long term fuel burnup reactivity loss.

3. Thermal Analysis. A finite element thermal analysis was performed on the core using the computer code ABAQUS. The results predict that under normal operating conditions the maximum core temperature is 640°C (for a reactor thermal power of 200 kWt, a graphite thermal conductivity of 71 W/mK, a heat pipe temperature of 580°C, and a gap ΔT of 10°C). These conditions produce an average core temperature of 630°C and a graphite ΔT of 50°C.

Table II is a list of core ΔT s that result from various operating scenarios, including operation with failed heat pipes. For the case of a single heat pipe failure the graphite ΔT increases to 100°C. If two adjacent heat pipes fail, the ΔT increases to 180°C. Although not detrimental to the reactor core, a few heat pipe failures result in reduced electrical output unless the heat pipes are replaced.

The temperature drop across the graphite-to-heat pipe gap is 10°C for a 0.03 mm radial He filled gap. Although initially at 0.2 mm during assembly, the gap nearly closes at reactor operating temperature due to differential thermal expansion of the graphite and the heat pipes. Filling the core with air instead of He results in a five-fold ΔT increase. However, air ingress must be prevented because at the normal operating core temperatures of about 630°C, the O_2 in the air will rapidly oxidize the graphite.

An investigation of core temperature excursions after shutdown was made. Under normal conditions, the heat pipes remove the

TABLE II

REACTOR SYSTEM PERFORMANCE WITH HEAT PIPE FAILURE

CALCULATIONS:

- o Max core ΔT no failures ~ 50 K
- o Max core ΔT one failure ~ 100 K
- o Max core ΔT two adjacent failures ~ 180 K

RESULTS:

- o No effect on system performance in meeting mission requirements

few kilowatts of decay heat and the core temperature drops rapidly. If it is assumed that the heat pipes are not operating at shutdown, the core temperature increases 20°C during the first few hours and then slowly decreases as heat flows through the vessel wall.

Preliminary analyses indicate that low stress levels exist in the core. The low heat deposition rate of 0.1 W/cm³ results in small temperature gradients and associated stress levels. Because the high energy neutron fluence over the life of the reactor is less than 10²⁰/cm², no swelling problem exists. The neutron fluence, however, does reduce thermal conductivity in the H-451 graphite block by 5% from 75 W/mK to 71 W/mK over the 20-year reactor life (2).

HEAT PIPES

Heat pipes are used to transfer reactor heat from the core to the hot shoes of the TE generators. These highly reliable, passive, nearly isothermal heat transfer devices contain no moving parts. Heat removal from the core is achieved by boiling the liquid potassium working fluid from the interior walls of the evaporator section of the heat pipe. The vapor, with its latent heat, flows out of the core to the condenser region of the heat pipe where the latent heat is removed. The heat then flows to the TEs encircling the heat pipes. Shown in Fig. 2 are the heat pipes, 19 total, each 3.2 cm O.D. with a 2 mm wall and total length of 4.4 m. The potassium liquid flows back to the evaporator region in the core through a thin screen wick structure, with an assist from gravity. The wall material is carbon steel electroplated inside and out with nickel (Ni). Although Ni/K heat pipes have proven quite successful in past experiments at RCA Corp. [40,000 h without failure (3)], the use of steel was necessitated by the high neutron absorption cross section of Ni. Using steel as the main wall material appreciably reduces the core ²³⁵U inventory. (A more satisfactory heat pipe design is being investigated.)

During normal operation in a power flattened core each heat pipe transfers 10.5 kWt. A considerable design margin exists because this power is a factor of three below the heat pipe sonic limit. The maximum radial heat flux through the evaporator wall is 8.7 W/cm², which is also far below design limits.

THERMOELECTRICS

Electric power is generated by thermoelectric elements. These passive devices produce electric power when a temperature gradient exists across them, in a manner

similar to a thermocouple. The TEs are arranged circumferentially around the heat pipes as shown in Fig. 7. The materials that are the most efficient generators in the temperature range of interest are lead-telluride (PbTe) for the "n" leg and tellurium-antimony-germanium-silver (TAGS) for the "p" leg. The "p" and "n" TE legs act so that their combined voltages add and thus increase electrical output. When assembled into a module, these elements generate 11 W at 12 VDC. With a height of 1.3 cm and a cross sectional area 10 cm^2 , an efficiency of about 9.7% is achieved for a 450°C hot-to-cold shoe ΔT (4). The design parameters for the TEs in this power supply are given in Table III. For a hot junction temperature of 545°C , the corresponding cold shoe temperature is 95°C . Maximum recommended continuous operating temperature for TAGS is 580°C , but little degradation occurs at 595°C . Therefore, a margin of 50°C exists under these temperature conditions. To raise the small voltage and power of each element to a useful level, series/parallel connections between elements are used. This is accomplished by using electrically conducting shoes on the hot and cold junctions. Insulators on the sides as well as outboard of the hot and cold junctions are also required. By judicious placement of conductors and insulators, the voltage is increased to a few hundred VDC and the power to 15 kWe. The PbTe/TAGS must be hermetically sealed to prevent air induced degradation.

TABLE III

THERMOELECTRIC PARAMETERS

Output/Module : 11 W, 12 VDC
Efficiency : 9.7%

MATERIAL

TE : PbTe (n) TAGS (p)
Hot shoe : Nickel
Cold shoe : Aluminum
Hot insulator : Mica
Side insulator : Mica
Cold insulator : Al_2O_3
(Anodized Aluminum)

TEMPERATURES

Maximum $^\circ\text{C}$	
Heat pipe	580
Heat pipe ΔT	5
Hot insulator ΔT	30
Hot shoe	545
Cold shoe	95
Cold insulator ΔT	10
Fin root	85
Average coolant air	25
Ambient air	20

PbTe/TAGS modules have been incorporated in many electric power generating devices. "Viking" and "Pioneer" satellites are still functioning satisfactorily after 15 years in space. Terrestrial generating units such as "Sentinel" continue to operate after 18 years.

HEAT REJECTION

In this power supply ambient air serves as the heat sink as it flows over a series of fins attached to the TE cold shoes. Figure 7 is a top, cross sectional view of the heat pipes, TEs, and heat rejection fins. Heat transfer from fins to air is by forced convection, in which the average turbulent heat transfer coefficient is $28 \text{ W/m}^2\text{C}$. Natural convection heat transfer without fans can be used in some applications. The aluminum fins are radially 10 cm long and 2 mm thick; 16 surround each heat pipe. Total axial fin length is 2.3 m, which is the length of the TE and condenser section of the heat pipes. Use of fins to augment heat transfer is quite effective in this design, where a 20-fold increase is realized.

CONTROLS

Reactivity is controlled by 18 control drums with B_4C absorber segments. As previously discussed, drum rotation is achieved by stepping motor actuators to produce the desired power level.

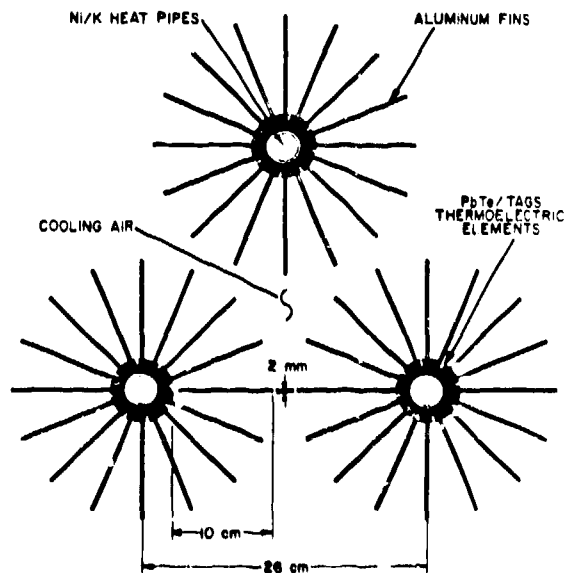


Fig. 7. Thermoelectric/heat pipe/cooling fin arrangement.

Heat pipe temperature provides a convenient reactor control parameter when the reactor is near normal operating power. Neutron flux control may be required at startup and at low power levels. Several temperature sensors are needed in the power supply to protect various components. These sensors have an override/reactor shutdown capability that can be activated either automatically or remotely by an operator.

A power controller is needed to regulate the small changes in power requirements of the load as well as shunt the 3 kWe of contingency power at BOL. This is achieved by shorting some of the TEs. The TE output voltage is DC at a level tailored to the load requirements, but AC power can be provided by a converter. The reactor is controlled by a computer housed nearby. Remote monitoring and shutdown of the power supply is possible, although the reactor can shut down in an autonomous manner.

SAFETY

The reactor power supply is a "walkaway safe" device. In any conceivable accident scenario the need for operator intervention is eliminated and the inherent safety features of the reactor will preclude significant risks to the public or environment. The very low ^{235}U inventory of 11 kg at 20% enrichment also serves to minimize safeguards problems.

The accident scenarios which generally show the greatest risk potential are loss of coolant (LOC) and transient overpower (TOP) without scram. The low power density of 0.1 W/cm^3 , the high heat capacity of the massive graphite core, the large negative temperature coefficient of reactivity, the redundant heat pipes in place of a primary coolant system, and the secondary shutdown system essentially eliminate the risk of both LOC and TOP.

A second criticality is defined as a series of events whose synergism produces a critical configuration of the core that is different from the original configuration. Second criticality is not possible in this reactor because the mass of 20% enriched ^{235}U is an order of magnitude too low. The reactor is only critical in its heterogeneous, moderated configuration. In this reactor, the low total power and low power density make decay heat removal a non-issue. The high heat capacity of the graphite and the low decay heat power (which drops fairly rapidly to less than 2 kW) result in a very slow rate of increase in the core temperature, less than 2°C per hour. Even if the reactor were insulated from the environment,

after a month no damaging fission product release temperatures would be achieved.

Because the reactor was designed for unattended operation without refueling, a reserve reactivity is required for startup. Three protective devices have been incorporated into the design. First, drum rotation is restricted to a very low rate by limiting devices. Second, total drum rotation angle will be restricted by pins which are removed as burnup proceeds. Third, burnable poison will be incorporated so as to minimize the excess reactivity. A secondary passive and independent shutdown mechanism is also provided in the form of B_4C balls that are released into the core when a fusible diaphragm melts at high temperatures.

MECHANICAL DESIGN

The reactor is hermetically sealed in a 1 cm thick steel vessel that serves to prevent air ingress, He egress, and inadvertent damage to the reactor during shipment. The reactor is pressurized with He slightly above atmospheric pressure. A pressurization system is used to store He as the reactor temperature rises during startup and to supply He as the reactor temperature and He pressure falls during shutdown. Should it be necessary, the vessel can serve as a secondary containment. Between the vessel and reflector is a 5 cm thick layer of fibrous insulation that reduces heat loss to a few kilowatts. The heat pipe-TE-fin portion of the power supply is structurally supported in a relatively thin 120 cm diameter cylindrical shell that provides ducting for coolant air, support, and protection during transportation. Table IV contains germane sizes and weights.

Although both the heat pipes and TEs have proved extremely reliable in numerous multiyear tests, provision was made for replacement through the use of flanges on the heat pipes and mating reseal devices on the vessel head. Replacement of actuators, fans, or He supply, although not anticipated, is quickly and easily performed. The redundancy of the aforementioned components allows for failures without the need for immediate or complicated maintenance.

SHIELDING

Neutrons and gamma rays produced in the core must be absorbed by shielding to protect personnel as well as vital parts of the system such as TEs, actuators, and sensing devices. The top of the reactor is partially shielded by a cadmium neutron absorber plate 2 mm thick and a lead gamma shield 10 cm thick as shown in Fig. 2. This thickness of lead reduces gamma flux from the reactor to

TABLE IV
SIZE AND WEIGHTS

Reactor	Size	Weights (kg)
Core	125 cm O.D.	2,670
Reflector	165 cm O.D.	3,470
Vessel	180 cm O.D.	1,280
<u>Heat Pipes</u>		130
Diameter	3.2 cm	
Length	4.4 cm	
<u>TE</u>		270
Diameter	5.8 cm	
Length	2.3 cm	
<u>Heat Rejection</u>		420
Fins	10 cm	
Length	2.3 m	
<u>Structure</u> <u>Actuator, etc.</u>		490
<u>Shield</u>	Pb and Cd	1,320
<u>Total Power Supply</u>		10,050
Diameter	1.8 m	
Height	4.6 m	

the actuators and TEs by a factor of 1000. Shielding for the top is completed by a 0.5 m thick concrete shield cap above the TEs. Shielding at the sides of the reactor is in the form of a borated concrete vault and local rock/earth if available. With a minimum of 3 m of rock/earth around the reactor, the gamma ray dose rate at the surface is reduced to <2 mR/h and neutron dose to near zero.

POWER RATING IMPROVEMENT

The basic design described in previous sections is flexible and robust in its power capabilities. The "stretch" capability of the reactor to higher power levels of 100-400 kW_e can be achieved at modest increases in fuel loading, size, and cost. The key to this capability is to replace the relatively inefficient and expensive thermoelectric power conversion system with a working fluid cycle. Figure 8 shows the basic heat pipe reactor design coupled to an organic Rankine cycle boiler and turboalternator. These hermetically sealed power conversion systems have demonstrated high reliability in remote, unattended conditions (mean time between failures in excess of 30,000 hours). The heat pipe boiler is a commercially available product frequently used in waste-heat recovery systems. Preliminary economic analyses indicate that this concept is commercially

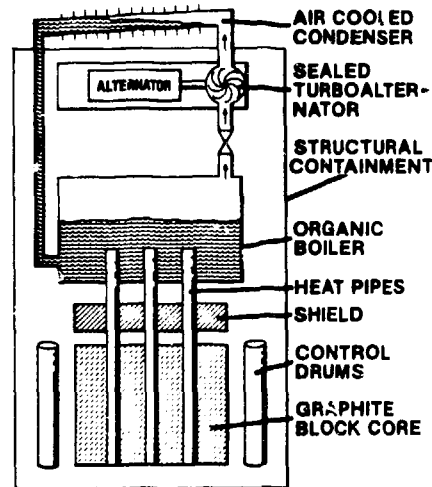


Fig. 8. Reactor power supply with organic Rankine cycle.

competitive for remote installations and settlements that have fuel oil costs in excess of \$4/gallon.

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REFERENCES

1. K. L. Meier, et al., "North Warning System Reactor Power Supply Description," Los Alamos National Laboratory report (to be published).
2. R. W. Schleicher, GA Technologies, Private Communication (2/84).
3. E. A. Skrabek, et al., "Heat Pipe Design Handbook," DRL-2, Dynatherm Corporation (August 1972).
4. P. J. Dick and W. M. Brittain, Teledyne Energy Systems, Private Communication (3/84).